21-cm Radio Astrophysics

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Our experiment was in two parts. The purpose of first half was to determine the temperature of the temperature and the purpose of the second half was to determine the velocity curve of the galaxy. For the solar temperature, we measured radio emissions from the sun and compared it to a known temperature signal. Using these two measurements, we calculated the temperature of the sun to be $530000 \pm 70000$ K. For the second half of the experiment, we measured the 21-cm hydrogen emission spectrum from the galactic equator. Using doppler shift equations, we were able to plot the velocity curve of the galaxy.

INTRODUCTION

The Milky Way is usually referred to as a rotating spiral galaxy. However, it actually consists of two separate components: a 3 kpc diameter spherical component consisting of older, smaller stars, and a 30 kpc diameter concentric disk “halo” as shown in Figure 1. Our solar system, Sol, is located in the disc component, approximately $8.0 \pm 0.5 kpc$ from the galactic center. In between the stars of the halo is the interstellar medium, which consists of gas (including hydrogen) and dust particles.

![Diagram of the Milky Way galaxy]

FIG. 1: The shape of the Milky Way galaxy, not to scale. Population I stars are older and smaller. Population II stars are a heterogeneous mix of older and newer, smaller and larger stars.

During World War II, H. Van de Hulst, a Dutch astronomer, was the first to predict that the spin flip transition of hydrogen in interstellar space would emit a photon of wavelength 21 cm. The number of transitioning hydrogen atoms is enough to create a spectral line of 21 cm or 1420.405 MHz (within radio range) and detectable on Earth. The line was first observed in 1951 by three different groups: Ewing and Purcell, Christiansen, and Muller and Oort.
Measurements of the doppler shift of the frequency of this line can be used to help determine the radial components of the galactic motion. By taking measurements at different points along the galactic equator, the plane of the disc component, we can determine a velocity curve of the galaxy.

For the first part of the experiment, we use radiation of the sun to determine its temperature. The sun acts as a blackbody, and we use the portion of energy emitted in the 21-cm wavelength range in our measurements. This energy spectrum does not come from spin-flip hydrogen, but rather is only a portion of the entire spectrum of solar radiation. We compare the energy spectrum to a known temperature (150 K) in order to determine the temperature.

THEORY

In order to calculate the temperature of the sun, the signal is compared to that of a known temperature, in this case 150 K. Since the sun and the antenna act as an extended point source to a circular aperture, the expected solar power spectrum is a Bessel function. However, since the sun is larger than a point source, the actual power spectrum is wider than a standard Bessel function.

For the galactic half of the experiment, the maximum red shift at each point is used to determine the velocity using the doppler equation:

\[
\frac{\Delta \nu}{\nu} = \frac{v}{c}
\]

(1)

This velocity is then associated with a radius based on the longitude, the trigonometry of which is shown in Figure 2. Since the maximum red shift occurs at the maximum velocity, the radius perpendicular to the longitude is one we measured:

\[ R = R_0 \sin(l) \]

(2)

where \( R_0 \) is the distance from the sun to the center of the galaxy and \( l \) is the galactic longitude measured.

![Maximum Red Shift Occurs at the Radius Tangent to Longitude Line](image)

FIG. 2: The trigonometry behind the relationship of longitude and radius of maximum red shift.

The angular velocity is then computed using the equation:

\[ \omega(R) = \frac{v \tan(l)}{R} + \omega(R_0) \]

(3)
where $v_{tan}$ is the velocity computed from the doppler shift equation and $\omega(R_0)$ is the angular velocity of the sun, $27.5 \, \text{km s}^{-1} \text{kpc}^{-1}$. The radial velocity is then:

$$\Theta(R) = R \omega(R)$$  \hspace{1cm} (4)

By computing $\Theta(R)$ for multiple $R$, we can determine the velocity curve of the galaxy.

**EXPERIMENT**

The experiment was performed on the roof of building 26 using a 2.5 meter diameter radio telescope, a low-noise receiver, and LabVIEW software as shown in Figure 3. The signal collected by the antenna was amplified and converted by heterodyning (signal mixing) from 1420 MHz to 122.6 MHz, amplified again and reduced to a bandwidth of 15 MHz centered on 122.5 MHz. The signal was then heterodyned again to produce a frequency of 42.5 MHz and sent through a 5 MHz wide filter. The frequency was then amplified and passed through an attenuator before an Agilent 8471D detector produced a voltage proportional to power, which was read by an A-D converter in the software.

![Diagram](image)

**FIG. 3:** Adapted from [1]. This is a schematic of the main apparatus. The radio signals were picked up by the antenna located on the roof of building 26. They were fed through signal processing, including heterodyning, before going to the computer to be analyzed using LabVIEW software. A sample signal for calibration was outputted with the Marconi Frequency Synthesizer.

For the solar spectrum, the telescope was aimed at the declination of the sun and an hour angle 30 minutes greater than the sun’s location. The spectrum was then taken over the course of an hour while the sun drifted across the telescope. A noise generator, set at 150 K, was turned on at five points during the spectrum in order to calibrate as shown in Figure 4. Calibration was done by stretching the curve in order for the five noise spikes to be at the same height, as shown in Figure 5.

For the galactic portion of the experiment, the calibration of output bin to frequency was needed. This was computed by using a Marconi Frequency Synthesizer to generate three different frequencies, 710.1025 MHz, 710.2025 MHz, and 710.3025 MHz. Since the detector cannot read signals less than 1 GHz, it was assumed that the second harmonic of the signals was measured, or 1420.205 MHz, 1420.405 MHz, and 1420.605 MHz. The output channel of
FIG. 4: The uncalibrated solar power spectrum. Note that the heights of the noise diode spikes are not the same.

FIG. 5: The calibrated solar power spectrum. Note that the heights of the noise diode spikes are the same.
These frequencies were plotted against themselves and a linear fit was used to determine the calibration of all bins to frequencies, as shown in Figure 6.

![Calibration of Bin to Frequency](image)

**FIG. 6:** The calibration curve of the channel number used in the software to frequency. The calibration was done by plotting known signals from the Marconi Frequency Synthesizer against their outputs. Since the frequencies used are less than 1 GHz, the second harmonic was actually taken, making the calibration: \( \text{Frequency} = \frac{\text{Bin}}{40} + 1419.0 \text{MHz}. \)

The software was also capable of moving the telescope to specified galactic latitudes and longitudes. We pointed the antenna at 10 different longitudes, ranging from 20 degrees to 110 degrees in intervals of 10 degrees each. For each longitude, two measurements were made: a background spectrum of the galactic equator and a sample spectrum on the galactic equator. The difference in these two spectrums was used as the hydrogen power spectrum shown in Figure 7.

**DATA AND ANALYSIS**

For the solar portion of the experiment, we calibrated the curve and measured the height of the power spectrum of the sun to be 9.2 cm \((H_S)\) while the height of the noise diode spike was 1.6 cm \((H_C)\). A ratio of these measurements multiplied by 150 K (the known temperature of the noise diode, \(T_C\)) should have given an approximate value of the temperature of the sun. However, the fact that the solid angle of the sun \((\Omega_S)\) does not entirely fill the solid angle of the telescope \((\Omega_A)\) also needed to be taken into account. A factor of two was also necessary since the antenna only measures the energy polarized in one direction while the sun emits radiation of all polarizations. Taking all these factors into account, the temperature of the sun was calculated as:

\[
T_S = 2 \frac{H_S}{H_C} T_C \frac{\Omega_A}{\Omega_S}
\]

The ratio of the solid angles was approximately 307, resulting in our temperature of the sun to be 530000\(\pm\)70000 K using uncertainties in the height measurements.

For each of the galactic longitudes measured, the maximum red shift was determined by computing an average noise value by averaging at least 30 points clearly in the noise range and taking the first point on the left most edge of the peak to go above 125 percent of that value. For the longitudes greater than 90 degrees, no red shift was observed because of the geometry of the galaxy. Looking at Figure 2, it is clear that an longitude greater than 90 degrees will not point towards the center of the galaxy.

For each longitude, the tangential velocity was calculated using equation (1) where \(\Delta \nu\) was found in the above method, \(\nu\) was 1420.405 MHz, and \(c\) is the speed of light. The radius corresponding to each longitude was calculated...
using equation (2). The angular velocity was computed using equation (3) and the radial velocity was computed using equation (4). The resulting velocities were plotted against the radius in Figure 8. The radial velocity curve was then plotted against the expected velocity curve from [2] as shown in Figure 9.

**CONCLUSIONS**

The temperature of the sun, as determined by our measurements, is $530000\text{K} \pm 70000\text{K}$. The surface of the sun averages $5400\text{K}$ and the corona can range up to $1000000\text{K}$. Since our value falls near the average of these two accepted values, our temperature is a reasonable approximation.

The velocity curve determined by our measurements qualitatively matches the expected velocity curve as reported in Ref. [2]. The points on our curve are all under the known curve. More than likely, this is because only a first order calculation was made. The velocity of the Earth around the Sun was not taken into consideration.

The curve is neither that of a uniform mass nor does it follow Keplerian laws. The galaxy is not homogeneous in mass distribution, necessary for the uniform mass curve, nor is the bulk of the galactic mass located at the center of the galaxy, necessary for Keplerian laws to take effect.
FIG. 8: The velocity curve of the galaxy, as determined by our measurements. The three curves represent tangential velocity with respect to the sun, angular velocity, and radial velocity.

FIG. 9: The expected velocity curve as shown is [2]. Our velocity curve is mapped onto the graph.
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